ANL-18/45

# Off-Road Vehicles Research Workshop

*Summary Report*

**Argonne National Laboratory**

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ANL-18/45

# Off-Road Vehicles Research Workshop

*Summary Report*

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Workshop hosted by:
Doug Longman and Essam Elhannouny
Center for Transportation Research (CTR), Argonne National Laboratory

Program Sponsored:
Gurpreet Singh and Mike Weismiller, DOE Managers
U.S. DOE, Vehicle Technologies Office

01/24/2019
Workshop Dates: October 25-26, 2018

## Acknowledgment

The authors would like to thank those individuals and industries who participated in the workshop and value their time and input.  We look forward to continuing the dialogue.

# Contents

## Abbreviations and Acronyms

| | |
|---|---|
| AEM | Association of Equipment Manufacturers |
| ANL | Argonne National Laboratory |
| CARB | California Air Resources Board |
| CFD | Computational Fluid Dynamics |
| CNG | Compressed Natural Gas |
| CNH | CNH Industrial N.V. |
| DOE | U.S. Department of Energy |
| EMA | Engine Manufacturers Association |
| EPA | Environmental Protection Agency |
| ES | Energy Systems Division (Argonne) |
| FEV | FEV North America, Inc. |
| GE | General Electric |
| GHG | Greenhouse Gas |
| LPG | Liquefied Petroleum Gas |
| LTC | Low-Temperature Combustion |
| MSOE | Milwaukee School of Engineering |
| NFPA | National Fluid Power Association |
| $NO_x$ | Nitrogen Oxides |
| NREL | National Renewable Energy Laboratory |
| ORNL | Oak Ridge National Laboratory |
| PNNL | Pacific Northwest National Laboratory |
| R&D | Research and Development |
| SCR | Selective Catalytic Reduction |
| SNL | Sandia National Laboratories |
| TRL | Technology Readiness Level |
| UMN | University of Minnesota |

## Executive Summary

This report summarizes the off-road vehicles stakeholder workshop that was focused on research, technical challenges, and future direction related to off-road vehicles and held at Argonne National Laboratory in October 2018. The views expressed in this report are those of the workshop participants. Topics discussed and included in this report are **engine efficiency and emissions**; **efficient fluid power**; **and system integration, control, and new technologies**. The purposes of this workshop were to: 1) Discuss and exchange information on the current state of technology for off-road vehicles; 2) Work collectively to address the technical challenges; and 3) Help shape the future direction for off-road vehicles research and development (R&D).

The report highlights some key points, takeaways, and technical challenges and ideas to inform DOE R&D programs for the off-road sector. The workshop objectives were to:

- Identify the barriers to cost-effective, high-efficiency, off-road vehicles;
- Identify pre-competitive research topics that could have the biggest impact in overcoming barriers; and
- Identify metrics that should be applied to program progress and ambitious but realistic goals.

Customer acceptance, reliability, and system durability are some of the market barriers to new technology that were discussed during the workshop. Participants agreed that a comprehensive strategy is required to explore ways to improve engine efficiency while lowering emissions (i.e., $NO_x$, GHG, etc.) and at the same time, meet customer needs and expectations. A full system optimization was recommended for off-road vehicles. It was noted that off-road vehicles are very diverse with a wide range of engine size and vehicle applications. A need for R&D for transient operations and other operating conditions was identified, as off-road vehicles are currently optimized for steady state. Fuel type for these vehicles has an important role. Fuel cost and fuel delivery to the work-site are challenging for any new fuel. Increased vehicle electrification is one of the new technologies discussed during the workshop. Electric propulsion for off-road vehicles has limited applications in the near term, but hybridization seems more promising. Furthermore, electrification requires better batteries and, possibly, the use of higher-voltage systems. Developing more efficient component technologies, including pumps, motors, and valves, is important for more efficient fluid power systems. New work-circuit architectures that can decrease throttling losses and better integrate the work circuit and engine can offer significant efficiency gains.

Autonomous vehicles for off-road sectors were also discussed. Autonomous vehicles for off-road space are very appealing for some markets due to shortage in skilled labor and its significant impact on productivity, vehicle weight, and therefore, energy use and emissions. Autonomous driving for mining and farming applications is more feasible because the routes are predefined, but for other applications, such as forestry and construction vehicles, autonomous driving would be very challenging.

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# Introduction

Efficient off-road vehicles are an important element of industries such as construction, agriculture, mining, and forestry. Technologies in these industries use the vast majority of the engine's mechanical energy to power hydraulic circuits that perform work such as moving the arm of an excavator or actuating a wheel loader bucket. Therefore, a deeper understanding of the whole system is essential to improve efficiency. This workshop brought together national laboratories, universities, and numerous industry and government stakeholders to discuss technical challenges and research opportunities for off-road vehicles. A full list of attendees is provided in Appendix B. The stakeholder distribution by sector attending this workshop is illustrated in Figure 1. The objectives of this workshop were to discuss and exchange information on the current state of technology for off-road vehicles; work collectively to address the technical challenges and opportunities; and help shape the future direction for off-road vehicle R&D. Stakeholder attendees were invited to share their thoughts, insights and opinions during the meeting. The workshop was conducted with two important points in mind:

- Stakeholder outreach should be used to inform U.S. Department of Energy (DOE) research programs; and
- Workshops should be a step toward defining metrics to measure program success.

A pre-workshop questionnaire was sent to all participants to incorporate their inputs during the discussion. As shown in Table 1, a total of 47 individuals responded. The questions and a summary of the results from this questionnaire is provided in Figure 2.

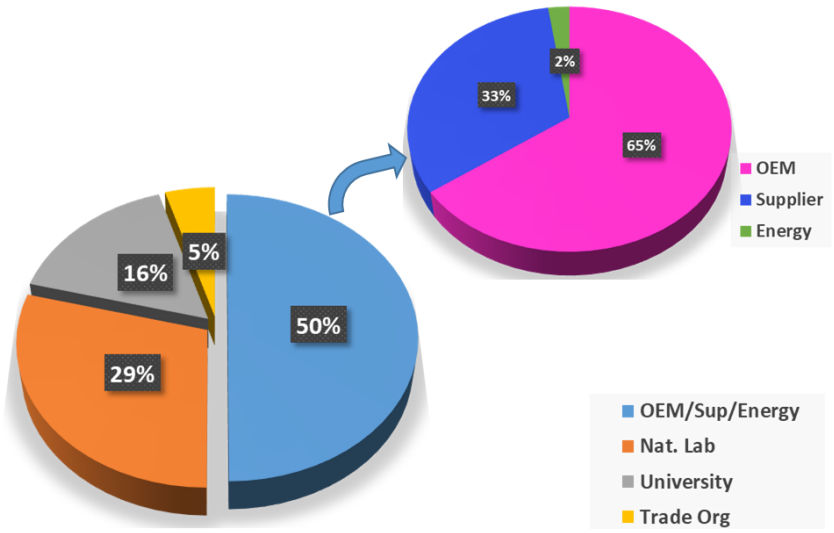


**Figure 1. Stakeholder Representation among Workshop Participants**

**Table 1. Survey Total Response and Distribution**

| ANSWER CHOICES | RESPONSES | |
|---|---|---|
| Trade organization | 4.26% | 2 |
| OEM | 31.91% | 15 |
| Supplier | 19.15% | 9 |
| National Laboratory | 19.15% | 9 |
| University | 25.53% | 12 |
| TOTAL | | 47 |

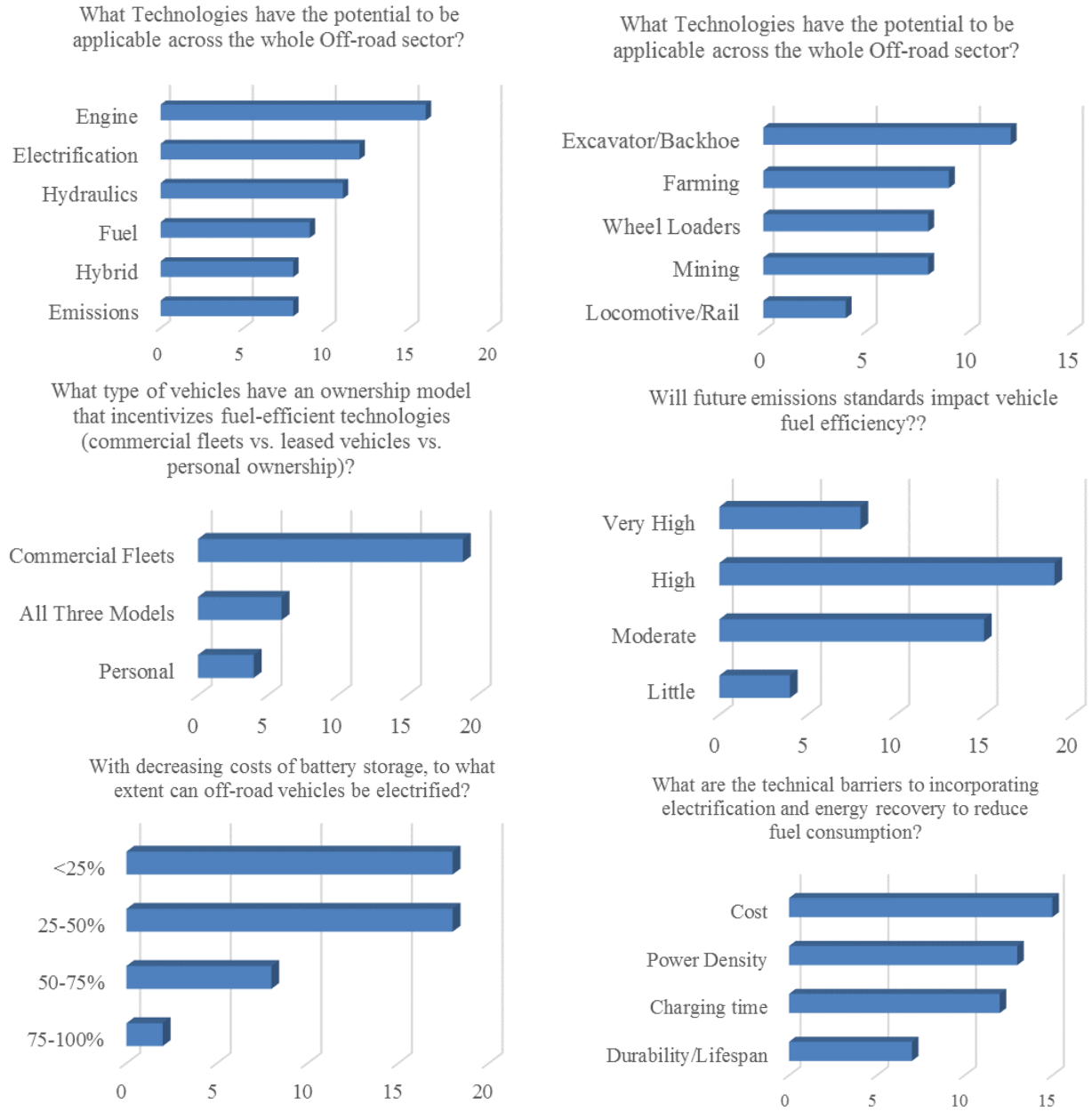


**Figure 2. Summary of Questionnaire Responses**

This summary report presents highlights from participant discussions covering the topics of engine efficiency and emissions; efficient fluid power; and system integration, controls and new technology. The variety of input gathered from the stakeholder attendees is vital, as it helps inform DOE's off-road R&D. Stakeholder feedback is balanced against DOE strategic direction and priorities with consideration of the roles of government and industry.

## Workshop Objectives

The three key objectives for this workshop were:

- Identify the barriers to cost-effective and high-efficiency off-road vehicles;
- Identify pre-competitive research topics that could have the biggest impact in overcoming barriers; and
- Identify metrics that should be applied to program progress and ambitious but realistic goals.

The workshop covered three topics related to off-road vehicles, namely **engine efficiency and emissions**; **efficient fluid power; and system integration, control, and new technologies**.

On the first day of the workshop, four companies and one trade organization presented their perspectives on the current status of off-road vehicle technology and technical challenges. On the following day, three breakout discussion sessions were held to identify key challenges and research opportunities for each area. The following sections provide a summary from each group discussion.

## 1. Engine Efficiency and Emissions

The majority of the engine efficiency and emission group participants agreed on the following:

- Off-road vehicles are very diverse with a very wide range of displacement and applications. Additionally, different markets have different priorities. It is important to distinguish between vehicle applications and powertrain duty cycles. It could be helpful to divide engines by use profiles and applications. For example:
    - Agriculture vs. construction equipment
    - Agriculture priorities, listed in order of importance, include initial cost, package size, reliability, durability, and fuel cost
    - Construction priorities, listed in order of importance, include fuel cost, reliability, durability, package size, and initial cost
    - Both of the above applications (markets) need minimal complexity and are risk-averse
- Off-road vehicles are highly optimized for steady-state.
- Transients and other operating conditions are big challenges. Off-road vehicles need full-system optimization similar to DOE's SuperTruck Program for on-road vehicles.
- There is a need for increasing engine efficiency by reducing thermal losses and increasing peak pressures. Computational Fluid Dynamics (CFD) and simulation tools could be very helpful in achieving improved engine efficiency during the design phase.

- Some of the off-road vehicles, such as locomotives, have a very long lifetime, typically 65 years in the field. For locomotive applications, fuel cost is of greater concern than the initial cost. Reliable power electronics and packaging are also among a few of the challenges for locomotive engines.
- The freight rail sector is the second-highest user of diesel fuel, after the freight trucks sector. Although most of the automotive and on-highway vehicle emissions and fuel economy technologies are applicable to locomotive engines, a complete product development cycle is required because of the sector's typical engine size, system integration complications, and operating conditions.
- A pre-competitive research effort to continuously develop fuel efficient technologies for the railroad sector should be considered.
- Retrofit/modular solutions could be valuable for off-road vehicles.
- Fuel type has an important role; however, cost and transporting fuel to the site are significant challenges for new fuels.
- Alternative fuels like compressed natural gas (CNG) and liquefied petroleum gas (LPG) are near-term solutions. Packaging is more challenging, but aftertreatment equipment could be simpler. Fuels used may differ by region.
- Thermal management of selective catalytic reduction (SCR) systems is still a challenge (cold-start and low-temperature combustion [LTC]) and further reductions in nitrogen oxide ($NO_x$) emissions will require a better understanding of real-world use.
- Further decreases in $NO_x$ standards will likely be coming from the California Air Resources Board (CARB) for on-highway and possibly off-road applications.
- The U.S. Environmental Protection Agency is not regulating greenhouse gas (GHG) emissions from off-road vehicles.
- There is a need to create a list of challenges addressing commonalities among different applications. Examples of these challenges include:
    - Transient operation conditions and low load operation
    - Low volume of off-road vehicles, which doesn't support the return on investment
    - Engine emissions and their impact on the environment
    - Fuel price uncertainty — only high fuel prices drive demand for high efficiency
    - Reluctance to accept new technologies if fuel price is low or stable; price differential in fuel price will drive demand for one fuel over the other
    - Fuel energy density and transporting fuel to point of use are important considerations
    - Aftertreatment location and low exhaust temperature conditions
    - Equipment must withstand pressure washing, high altitude, high shock loading, and wide ambient temperature operations

    - Applications involve a variety of duty cycles and often highly transient operations
    - Frequent transitions from low to high power causes fatigue from mechanical and thermal cycles
- Enabling technologies and future opportunities include:
    - Combustion system improvements, powertrain development, waste heat recovery, efficient air handling and accessories, idle efficiency, and aftertreatment systems
    - Target vehicles and markets: Probably best opportunities in mining vehicles, rail, large agriculture, and large construction equipment
    - Connectivity and automation
    - Powertrain and machine integration
    - Electrical charging or refueling, engine and vehicle control in most efficient manner; consider real-time and adaptive control optimization
    - Prognosis for failure avoidance
    - Fuels: Address challenges in adoption of lower carbon and renewable fuels
- Find/use ideas/technologies from on-road (highway) vehicles. On-road technologies can be scaled up or down for off-road engines. It is generally accepted that off-road engines under 15 liters can readily adopt technologies from on- road engines. Participants think that it could be beneficial to organize/rank the technologies that might be useful to address identified off-road challenges (rank/ordering applications).
- It might be helpful to create a problem statement, for example, “improve efficiency while decreasing emissions and at the same time meeting the customer needs.”
- Form a steering committee/group (or maybe a consortium) to identify the top 10 challenges and opportunities. Find solutions/opportunities for these challenges and match it.

## 2. Efficient Fluid Power

The fluid power group discussed several topics related to efficient fluid power systems and identified the following challenges and opportunities for new system architectures that are able to:

- Reduce parasitic and throttling losses
- Integrate components (engine/pump; electric/hydraulic solutions)
- Decouple hydraulic pumps from engine speed
- Disable work circuits when not in use
- Distribute hydraulic systems
- Develop more efficient component technologies — pumps, motors, valves

    - Explore additive manufacturing and new materials for component prototyping and construction
- Use “smart” technology to increase control and efficiency — there is a need for:
    - Inexpensive and reliable sensors
    - Real-time monitoring for optimizing component performance
- Advanced fluids that can increase energy efficiency — there is a need to:
    - Examine the impact on pump wear and the need for new materials/coatings with low viscosity grade and high viscosity index fluids
    - Co-develop fluids and components with smart materials and coatings to improve system efficiency
- Increase energy density of fluid power energy storage to facilitate cost-effective hybridization by:
    - Reducing accumulators size and weight
    - Exploring non-traditional energy storage technologies
- Develop elementary metrics for systems, components, and fluids that incorporate steady-state and dynamic conditions. For example, metrics for torque and speed for rotary output in steady-state, ramp-up, and ramp-down conditions. This would allow comparison of different architectures and components without linking to specific mission profiles.
- Low cost share for low technology readiness level (TRL) projects could promote more university research.

## 3. System Integration, Control, and New Technologies

The third discussion group concluded the following for system integration, control, and new technologies:

- New technologies need to instill trust. Any new technology needs to be as productive as the current ones or better.
- Hydraulic hybrids are a fairly mature market and do not represent a big research opportunity.
- Electric propulsion has limited applications. Fuel cells could be a solution but not in the near term, hybridization seems more promising.
- Electrification requires better batteries and possibly the use of higher voltage systems. Cost is an obstacle. Need to lower the battery cost to ~$80/Kwh to be attractive. A 48-volt electric system could be an enabler to electrification of hydraulics.
- Electric-hydraulic hybrids could combine the benefits of both electric and hydraulic storage and greatly reduce throttling losses.
- Advanced controls need to be specialized for different applications.
- A set of precompetitive simulation tools, such as an off-road version of Autonomie, is desirable to explore the following:

    - Duty cycles to compare against
    - Electrification versus hydraulics systems trade-off studies, tillage tools efficiency
- CFD analysis of after treatment, exhaust, air intake, cooling fans, etc. is also an important research area.
- Off-road vehicles operate on deformable media (e.g., soil), in which substantial energy losses occur when power is delivered for developing traction and propulsion. Improvement in motion resistance and traction efficiency could provide double-digit efficiency gains, and opportunities exist for development of precompetitive tools.
- Efficiency of fluid power should not be viewed only from the component side. A system can have highly efficient components but in a poor configuration, the system efficiency will be poor.
- Safety of autonomous vehicles: there is interest in autonomous vehicles due to a shortage of skilled labor. Autonomous vehicles will have a significant impact on farm productivity; they will also reduce weight and engine emissions.
- Autonomous vehicles require the following:
    - Sensing technologies, object recognition, connectivity, safety, security, and database object recognition
    - For mining and farming: Autonomous driving is more important because the routes are predefined. However, forestry equipment is often used on very steep slopes, which is very challenging
- Standards need to keep pace with technology development.
- Need for new fluid power virtual tool. Expertise on the design of these components is very rare and over time, the industry has experienced a large competence decay in the field.
- Mathematical equations for numeric simulation with some level of verification and/or validation are recommended to support DOE proposals for technology research & development.
- Using connectivity to improve control could require inexpensive and reliable sensors and better monitoring and optimization software.
- Need to develop metrics that can be used across the broad range of products.
- One of the most important challenges in realizing digital pumps and motors is the development of high-speed on/off valves. There is a challenging tradeoff between switching speed, flow rate, and actuation power. Overcoming this tradeoff could greatly facilitate improvements in hydraulic system efficiency.

## Appendix A: Workshop Agenda

### Day 1: October 25, 2018

| Time | Session (main room-1416) | Presenter |
|---|---|---|
| **1:00–1:05** | Introduction, Agenda Review, Attendee intro. | ANL: D. Longman, Manager |
| **1:05–1:10** | Welcome to Argonne National Laboratory | ANL Director Paul Kearns |
| **1:10–1:15** | Argonne Center for Transportation Research | ES Director: D. Hillebrand |
| **1:15–1:30** | Welcome and Meeting Objectives | DOE Managers:<br>G Singh/M. Weismiller |
| **Focus**: Current state of the off-road vehicle technology and technical challenges.<br>**Topics**: Engine Efficiency and Emissions; Efficient Fluid Power; and System Integration, Control, and New Technologies | | |
| **1:30–2:00** | Truck & EMA | Matt Spears |
| **2:00–2:30** | CNH | Gary Kassen |
| **2:30–3:00** | Cummins | Tim Lutz |
| **3:00–3:30** | Coffee break | |
| **3:30–4:00** | Progress Rail | Reddy Sankara |
| **4:00–4:30** | J. Deere | John N. Chi |
| **4:30–5:00** | Open Thoughts for Next Day…….. | ANL: D. Longman, Manager |
| **7:00-…** | ***Networking Dinner(optional, not sponsored)**** | NA |

*http://www.3cornersgrill.com/downers-grove/ 7231 LEMONT RD. DOWNERS GROVE, IL 60516, PHONE: 630.541.6700

Optional Tour #1 to Argonne Leadership Computing Facility Machine Room and Visualization Lab (from 5:15-5:45 and 5:45 to 6:15PM), tour guide: David, Janet and Roberto.

## Day 2: October 26, 2018

| Time | Session (main room-1416) | | Presenter |
|---|---|---|---|
| **8:00–8:30AM** | Breakfast/Networking | | NA |
| **Breakout Discussions** | | | |
| **Time** | **Group 1 (Rm 1416)**<br>**Engine Efficiency and Emissions**<br>*(MCs: M. Spears, EMA & M. Pankonin, AEM)* | **Group 2 (Rm 1404-05)**<br>**Efficient Fluid Power**<br>*(MC: E. Lanke, NFPA)* | **Group 3 (Rm 1406-07)**<br>**Sys. Integration /Control/New Tech.**<br>*(MC: M. Gust, UMN)* |
| **8:30–9:00 (5min/Co.)** | 1. Cummins, Azur Loye<br>2. CAT, K. Duffy<br>3. Achates, F. Redon<br>4. GE, A. Klingbeil<br>5. J Deere, B. Bratvold<br>6. SNL, C. Mueller | 1. CNH, G. Kassen<br>2. J Deere, J. Chi<br>3. MSOE, P. Michael<br>4. UMN, K. Stelson<br>5. ANL, Ali Erdemir<br>6. ANL, G. Fenske | 1. AEM, M. Pankonin<br>2. CNH, R. Stoltman<br>3. J Deere, A Appleton<br>4. BoschRexroth, Enrique<br>5. Servotechinc. S Hussain<br>6. FEV, D. Bandyopadhyay |
| **9:00–10:30** | Open discussion/Summary | Open discussion/Summary | Open discussion/Summary |
| **10:30–11:00** | ***Coffee break*** | | |
| **11:00–11:30** | Conclusions/Findings from Breakout sessions | | 3 MCs / 10min each |
| **11:30–12:00** | Concluding Remarks and Moving Forward<br><br>Thank you… | | 1-DOE Manager: Mike Weismiller<br>2-ANL Manager Doug Longman |

Optional Tour #2: Advanced Photon Source, C. Powell, Engine facility 371 C. Kolodziej/E. Rask, Tribology Lab 212 B. Erck, from 12:15PM to…

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*Program Sponsored by: U.S. DOE, Vehicle Technologies Office: Gurpreet Singh and Mike Weismiller, DOE Managers*

*Hosted by: Center for Transportation Research (CTR), Argonne National Laboratory: Doug Longman and Essam Elhannouny*

## Appendix B: Off-Road Vehicles Research Workshop Attendees List

| | First Name | Last Name | Organization |
|---|---|---|---|
| 1 | Oyelayo | Ajayi | ANL |
| 2 | Omowoleola | Akinyemi | General Electric |
| 3 | Cody M | Allen | Purdue University |
| 4 | Andy Blaine | Appleton | Deere and Company |
| 5 | Guy | Babbitt | Czero, Inc |
| 6 | Deep | Bandyopadhyay | FEV North America, Inc. |
| 7 | Timothy A | Bazyn | Caterpillar, Inc. |
| 8 | Randy Lee | Bergstedt | Cummins, Inc. |
| 9 | Brian H | Bratvold | John Deere |
| 10 | Enrique | Busquets | Bosch-rexroth |
| 11 | Marcello | Canova | Ohio State University |
| 12 | Sabri | Cetin | Servotech Inc. |
| 13 | John N | Chi | John Deere |
| 14 | Lelia | Cosimbescu | PNNL |
| 15 | Kevin P | Duffy | Caterpillar |
| 16 | Aleksandar M | Egelja | Caterpillar Inc. |
| 17 | Essam | El-Hannouny | ANL |
| 18 | Jacob | Erbe | Yanmar America Corp |
| 19 | Robert | Erck | ANL |
| 20 | Ali | Erdemir | ANL |
| 21 | Osman | Eryilmaz | ANL |
| 22 | James J | Faletti | Caterpillar, Inc. |
| 23 | George | Fenske | ANL |
| 24 | Sara Maria | Feuling | Association of Equipment Manufacturers |
| 25 | Vincent | Freyermuth | ANL |
| 26 | Xiao | Fu | Progress Rail |
| 27 | Jose M | Garcia-Bravo | Purdue University |
| 28 | Michael B | Goetzke | Progress Rail Locomotives |
| 29 | Michael J | Gust | University of Minnesota |
| 30 | Carrie | Hall | Illinois Institute of Technology |
| 31 | Don | Hillebrand | ANL |
| 32 | Mark Aaron | Hoffman | Auburn University |
| 33 | Keven W | Hofstetter | Caterpillar Inc. |
| 34 | David B | Horne | Yanmar America Corp |
| 35 | Syed Ameenuddin | Hussain | Servotech Inc. |
| 36 | Gary Roger | Kassen | CNH Industrial |
| 37 | Adam E | Klingbeil | General Electric |
| 38 | Chad Palmer | Koci | Caterpillar, Inc. |

| | First Name | Last Name | Organization |
|---|---|---|---|
| 39 | Rajeev | Kumar | ExxonMobil |
| 40 | Chris | Kolodziej | ANL |
| 41 | Eric F | Lanke | National Fluid Power Association |
| 42 | Andrew Michael | LeClair | Mississippi State University |
| 43 | Kevin | Lingenfelter | Danfoss Power Solutions |
| 44 | Doug | Longman | ANL |
| 45 | Jason A | Lustbader | NREL |
| 46 | Tim | Lutz | Cummins, Inc. |
| 47 | George L | Mason | Mississippi State University |
| 48 | Perla | Mendez | Trelleborg Sealing Solutions |
| 49 | Paul W | Michael | Milwaukee School of Engineering |
| 50 | Yanbin | Mo | CNH Industrial |
| 51 | Charles J | Mueller | SNL |
| 52 | Michael | Pamminger | ANL |
| 53 | Michael Scott | Pankonin | Association of Equipment Manufacturers |
| 54 | Vasudha | Patri | ANL |
| 55 | Mark S | Pickett | Czero, Inc. |
| 56 | David Andrew | Piech | CNH Industrial |
| 57 | Neng | Piyabongkam | Eaton Corporation |
| 58 | Reddy | Pocha Siva Sankara | Progress Rail |
| 59 | Christopher | Powell | ANL |
| 60 | Jun | Qu | Oak Ridge National Lab |
| 61 | Ram | Vijayagopal | ANL |
| 62 | Fabien Georges | Redon | Achates Power |
| 63 | Christopher V | Rebolloso | FPT Industrial |
| 64 | Terres A | Ronnenberg | SMI, Inc. |
| 65 | Stephen P | Rubenstein | Tenneco |
| 66 | Dileep | Singh | ANL |
| 67 | Gurpreet | Singh | DOE |
| 68 | Som | Sibendu | ANL |
| 69 | Mathew William | Spears | Truck and Engine Manufacturers Association |
| 70 | Aaron B | Stachewicz | McLaren Engineering - Linamar |
| 71 | Kim A | Stelson | University of Minnesota |
| 72 | Igor | Strashny | Caterpillar, Inc |
| 73 | Brian L | Steward | Iowa State University |
| 74 | Russsell V | Stoltman | CNH Industrial |
| 75 | John M | Story | ORNL |
| 76 | Natarajan | Suresh Babu | Parker Hannifin |
| 77 | Panos | Tamamidis | CNH Industrial |
| 78 | Roberto | Torelli | ANL |

| | First Name | Last Name | Organization |
|---|---|---|---|
| 79 | Punit J | Tulpule | Ohio State University |
| 80 | Jason L | Van Farowe | Caterpillar, Inc. |
| 81 | Andrea | Vacca | Purdue University |
| 82 | Kumaraswamy | Vellakal Chidambara | University of Illinois |
| 83 | Michael | Weismiller | DOE |
| 84 | Wenhua | Yu | ANL |
| 85 | Qinghui | Yuan | Eaton Corporation |
| 86 | Axel O | zur Loye | Cummins, Inc. |

Group photo of the workshop participants

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